Radio Frequency Integrated Circuits and Systems

Second Edition

This updated and expanded new edition equips students with a thorough understanding of the state of the art in RF design and the practical knowledge and skills needed in industry. Introductory and advanced topics are covered in depth, with clear, step-by-step explanations, including core topics such as RF components, signals and systems, two-ports, noise, distortion, low-noise amplifiers, power amplifiers, and transceiver architectures. New material has been added on wave propagation, skin effect, antennas, mixers and oscillators, and digital PAs and transmitters. Two new chapters detail the analysis and design of RF and IF filters (including SAW and FBAR duplexers and *N*-path filters), phase-locked loops, frequency synthesizers, digital PLLs, and frequency dividers. Theory is linked to practice through real-world applications, practical design examples, and exploration of the pros and cons of various topologies. Over 250 homework problems are included, with solutions and lecture slides for instructors available online. With its uniquely practical and intuitive approach, this is an essential text for graduate courses on RFICs and a useful reference for practicing engineers.

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To my family

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PREFACE TO THE SECOND EDITION

While the first edition was written to be equally used as a textbook in graduate-level RF courses in academia, as well as among RF professional engineers, it was felt that it may be more suitable to practicing RF engineers in industry. Personal teaching experience in the past few years and feedback from some colleagues and friends inspired me to work on a new edition to address the needs of entry-level graduate and senior undergraduate students more properly. To that extent, without altering the overall organization of the book significantly and retaining the bulk of material from the first edition, the book has been rewritten to address the fundamental concepts more deeply, give more step-by-step design explanations, and provide many more examples and clarifying points. The examples particularly are designed to cover both fundamental theoretical concepts as well as hands-on circuit-level design and simulations and have been organized more distinctly to both complement the basic concepts and provide guidelines for more advanced discussions. It has been the author's intention to familiarize the readers early on with two of RF designers' best friends, Spectre-RF and EMX, through many of these examples covering circuit-level analysis followed by verification through actual simulations. Furthermore, over 50 new additional problems, with guidance and hints, have been added throughout the 12 chapters and may be assigned as homework problems or exam questions or simply used as means of practicing the fundamental concepts.

Apart from this main motivation, there were several important concepts crucial in the RF design that were missing from the first edition or at least needed more elaboration. One of the main additions of this edition is the inclusion of two new chapters, one to cover in-depth analysis and design of RF and IF filters, including SAW, FBAR, duplexers, and *N*-path filters, as well as a dedicated chapter to cover phase-locked loops, frequency synthesizers, digital PLLs, and frequency dividers. Additionally, new discussions on wave propagation, skin effect, and antennas were added to Chapter 1. This is introductory material but is deemed vital for RF engineers as they are an essential part of RF design. Among other new additions are more expanded discussion on RF two-ports and reciprocal networks, additional discussions of mixers and oscillators, and a section on digital power amplifiers. One of the main innovations of this edition is inclusion of a section to address signal and power integrity, a critical part of the RF design. This was added to the low-noise amplifiers chapter, as being the most susceptible block, though is applicable in general to any part of the radio. It covers various topics such as electric and magnetic coupling, shielding, and power rails transient noise.

Neither in the first edition nor in the current one does a dedicated chapter on the subject of the wireless standards exist. The wireless standards are evolving, and as such a chapter examining them would be drastically different today versus five or ten years in the future. It is more important for RF designers to attain the ability to translate high-level system specifications into circuit-level requirements rather than memorizing the standard itself. This is fully addressed in Chapter 5 and especially Chapter 6, along with numerous references to the existing mainstream RF standards.

I have been very fortunate to enjoy the company of many talented individuals at Broadcom, from whom I have learned tremendously in my 20-year tenure there. I am thankful to all of them. I would like to specifically thank the following Broadcom colleagues and friends who helped proofread various chapters of the new edition: Wei-Liat Chan, Yuyu Chang, Saeed Chehrazi, Matteo Conta, Milad Darvishi, Valentina Della Torra, Dale Douglas, Mohyee Mikhemar, David Murphy, Bevin Perumana, and Hao Wu. I am also thankful to Dr. Ed Chien, who helped on the PLL chapter in general with many useful discussions, and particularly for his guidance on the digital PLL section. Likewise, thanks to Dr. Mikhemar, who co-wrote the digital PA section, and Dr. Rich Ruby, who provided valuable feedback on the SAW and FBAR section. I would also like to thank my teammates in Broadcom, Saeed Chehrazi, Milad Darvishi, Daivd Murphy, and Hao Wu, with whom I have had many useful discussions on various topics, directly or indirectly related to the book.

I am grateful to my Ph.D. advisor with whom I have kept close contact throughout the years, Prof. Asad Abidi from UCLA, who has been a great inspiration. I have benefitted tremendously from his insights and innovative teaching methods in general, and particularly in many sections of the book. I would also like to acknowledge my undergraduate instructor from Sharif University, Prof. Masood Jahanbegloo, a UCLA alumnus himself, for his dedicated teaching, and to whom I owe my fundamentals of basic circuit theory and electronics.

Lastly, I would like to thank my wife, Dr. Shahrzad Tadjpour, for her patience and technical feedback, and my family for their support.

PREFACE TO THE FIRST EDITION

In the past 20 years, radio frequency (RF) integrated circuits in CMOS have evolved dramatically, and matured. Started as a pure research topic in mid-1990 at several universities, they have made their way into complex systems-on-a-chip (SoCs) for wireless connectivity and mobile applications. The reason for this dramatic evolution comes primarily from two main factors: the rapid improvement of CMOS technology and innovative circuits and architectures. In contrary to the common belief that RF and analog circuits do not improve much with technology, a faster CMOS process has enabled a number of topologies that have led to substantially lower cost and power consumption. In fact to some extent, the recent inventions may not have been possible if not for better and faster technology. This rapid change has caused the modern RF design to be somewhat industry-based, and consequently it is timely, and perhaps necessary, to provide an industry perspective. One main goal of this book has been to cover possibly fewer topics but in a much deeper fashion. Even for RF engineers working on routine products in industry, a deep understanding of fundamental concepts of RF IC design is very critical, and it is the intention of this work to break this gap. During the course of writing the book, I have tried to address the topics that I would have wanted as a *wish list* for my fellow future colleagues. Our main focus then has been to elaborate the basic definitions and fundamental concepts, while an interested designer with a strong background can explore other variations on his or her own.

The contents of this book stem largely from the RF courses taught at the University of California, Los Angeles and Irvine, as well as many years of product experience at Broadcom. Accordingly, the book is intended to be useful both as a text for students and as a reference book for practicing RF circuit and system engineers. Each chapter includes several worked examples that illustrate the practical applications of the material discussed, with examples of real-life products and a problem set at the end to complement that.

RF circuit design is a *multidisciplinary* field where a deep knowledge of analog integrated circuits, as well as communication theory, signal processing, electromagnetics, and microwave engineering is crucial. Consequently, the first three chapters as well as parts of Chapter 4 cover selected topics from the aforementioned fields, but customized and shaped properly to fit the principles of RF design. It is, however, necessary for the interested students or RF engineers to have already taken appropriate senior-level undergraduate courses.

An outline of each chapter is given below along with suggestions for the material to be covered if the book is to be used for a 20-lecture quarter-based course. Furthermore, in the beginning of each chapter a list of specific items to be covered as well as more detailed suggestion of which sections to include for the class use are outlined. For beginner and intermediate practicing engineers we recommend following the selected topics suggested for the class use, while more advanced readers may focus on the other topics assigned for reading.

Chapter 1 contains a review of basic electromagnetic concepts and particularly the inductors and capacitors. Among many students and RF engineers, often the basic definition of capacitors and inductors is neglected, despite using them very regularly. A short reminder is deemed necessary. Furthermore, some basic understanding of Maxwell's equations is needed to understand transmission lines, electromagnetic waves, the antenna concept, and scattering parameters. These are discussed in Chapter 3. The chapter also gives an overview of integrated inductors and capacitors in modern CMOS. Two lectures are expected to be needed to cover the basic concepts.

Chapter 2 deals with basic communication and signal processing concepts, which are a crucial part of RF design. The majority of the material is gathered to provide a reminder and may be left to be studied outside the class, depending on the students' background. However, we cannot emphasize enough the importance of them. Spending a total of two or three lectures on the stochastic processes, modulation section, as well as a brief general reminder of passive filters and Hilbert transform may be helpful.

Chapter 3 is concerned with several key concepts in RF design such as available power, matching topologies, transmission lines, as well as scattering parameters and complements Chapter 1. Two lectures may be dedicated to cover the first three sections, while the more advanced material on transmission lines, the Smith chart, and scattering parameters may be very briefly touched or omitted altogether depending on the students' background.

In Chapter 4 we discuss, noise, noise figure, sensitivity, and an introduction to phase noise. The introductory part on types of noise may be assigned as reading, but the noise figure definition, minimum noise figure, and sensitivity sections must be covered in full. A total of two or three lectures suffices.

Chapter 5 covers the distortion and blockers. A large portion of this chapter (as well as Chapter 10) may be left for a more advanced course, and one lecture should suffice to cover only the basic concepts. However, the material may be very appealing to RF circuit and system engineers who work in industry. A thorough knowledge of this chapter is crucial to understand Chapter 10.

Chapters 6 to 9 deal with the RF circuit design. Chapter 6 is mostly built upon the concepts covered in Chapters 3 and 4 and deals with low-noise amplifiers. Three lectures may be dedicated to cover most of the topics presented in this chapter.

Chapter 7 provides a detailed discussion on receiver and transmitter mixers. Roughly two lectures may be dedicated to this chapter to cover basic active and passive topologies with some limited discussion on noise. The majority of the material on M-phase and upconversion mixers may be assigned as reading.

Chapter 8 discusses oscillators, including LC, ring, crystal oscillators, and an introduction to phase-locked loops. The chapter is long, and the latter three topics may be assigned as reading, while two lectures could be dedicated to LC oscillators, and a brief introduction to phase noise. A detailed discussion of phase noise is very math intensive, and may be beyond the scope of an introductory RF course. Thus, it may be sufficient to focus mostly on the premises of an abstract linear oscillator, and summarize Bank's general results to provide a more practical perspective.

Power amplifiers are discussed in Chapter 9. Basic classes are presented in the first few sections, followed by efficiency improvement and linearization techniques. Most of the material on the latter subject may be skipped, and one or two lectures may be assigned to cover a few examples of classes (perhaps only classes A, B, and F), as well as the introductory material on the general concerns and the trade-offs.

Finally, in Chapter 10 transceiver architectures are presented. This is one of the longest chapters of the book, and much of the material can be assigned as reading. The last section covers some practical aspects of the design, such as packaging and production issues. It presents a few case studies as well. The topics may be appealing for practicing RF engineers, but the entire section may be skipped for class use. A maximum of two lectures is sufficient to cover selected key transceiver architectures.

I have been very fortunate to be working with many talented RF designers and instructors throughout my carrier at UCLA, and subsequently at Broadcom. They have had an impact on this book one way or another. However, I wish to acknowledge the following individuals who have directly contributed to the book: Dr. David Murphy from Broadcom who co-wrote most of Chapter 8, and provided very helpful insight on Chapter 6, particularly the LNA topologies; Dr. Ahmad Mirzaei from Broadcom as well, who helped on the write up of sections of Chapters 9 and 10, and proofread the entire book painstakingly. They both have been major contributors to this book beyond the chapters mentioned. I would also like to thank Dr. Hwan Yoon from Broadcom with whom I had numerous helpful discussions on Chapter 1 material, and particularly the integrated inductors. My sincere thanks go to Prof. Eric Klumperink of the University of Twente, who proofread most of the book diligently, and provided valuable insight on various topics. I would also like to acknowledge my sister Hannah, who helped design the book cover. Lastly, I wish to thank my wife, Shahrzad Tadjpour, not only for her technical feedback on the book, but for her general support throughout all these years.

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GLOSSARY

ACLR	alternate adjacent channel leakage ratio
ADC	analog-to-digital converter
AM	amplitude modulation
BALUN	balanced-unbalanced
BJT	bipolar junction transistor
BNC	Bayonet Neill–Concelman
BPF	bandpass filter
BT	Bluetooth
BW	bandwidth
CG	common-gate
CMOS	complementary metal-oxide semiconductor
CP	charge pump
CS	common-source
DAC	digital-to-analog converter
dBc	decibels relative to the carrier
DSB	double sideband
DSP	digital signal processor
DUT	device under test
EDGE	enhanced data rate for GSM evolution
EMF	electromotive force
ENR	excess noise ratio
EVM	error vector magnitude
FBGA	fine-pitch ball grid array
FDD	frequency division duplexing
FDMA	frequency division multiple access
FET	filed effect transistor
FM	frequency modulation
FSK	frequency shift keying
GSM	global system for mobile communications
HD	harmonic distortion
HPF	highpass filter
IF	intermediate frequency
IMN	*N*th-order intermodulation
IO	input/output
IPN	*N*th-order intermodulation product

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More Information

I/Q	in/quadrature phase
ISM	industrial–scientific–medical
LNA	low-noise amplifier
LO	local oscillator
LPF	lowpass filter
LTE	long-term evolution
MATLAB	matrix laboratory
NB	narrowband
NF	noise figure
OFDM	orthogonal frequency division multiplexing
OOB	out of band
P1dB	1 dB compression point
PA	power amplifier
PAPR	peak-to-average power ratio
PCB	printed circuit board
PD	phase detector
PDF	probability distribution function
PFD	phase-frequency detector
PGA	programmable gain amplifier
PLL	phase-locked loop
PM	phase modulation
PPM	parts per million
PTAT	proportional-to-absolute temperature
QAM	quadrature amplitude modulation
RDL	redistribution layer
RMS	root mean square
RSSI	received signal strength indicator
RX	receiver
SAW	surface acoustic wave
SNR	signal-to-noise ratio
SSB	single sideband
TDD	time division duplexing
TDMA	time division multiple access
TIA	transimpedance amplifier
TR	transmit–receive
TX	transmitter
VCO	voltage-controlled oscillator
WB	wideband
WCDMA	wideband code division multiple access
Wi-Fi	wireless fidelity
WLAN	wireless local area network
XO	crystal oscillator